Development of All-sky GMI Radiance Data Assimilation Global Products from the GEOS-5 System in Support of the GPM Mission

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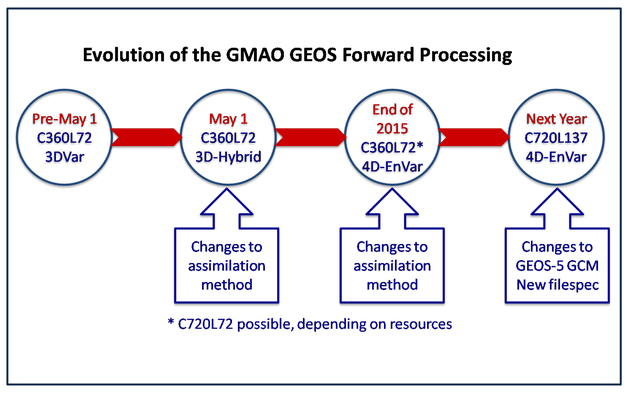
1. Introduction

• Data assimilation, which combines the information from observations and a short-range forecast, is a powerful tool to estimate the initial state of the atmosphere for NWP forecasts. Assimilating satellite observations from microwave imagers such as the GMI in cloudy and precipitating regions can provide critical constraints on meteorological parameters in dynamically sensitive regions and make significant impacts on forecast accuracy for precipitation.

• To expand the existing capabilities assimilating satellite radiance data in clear-sky condition, the NASA GMAO has been pursuing efforts to utilize all-sky (clear+cloudy+precipitating) microwave radiance data in the GEOS-5 ADAS. Assimilating surface affected microwave radiance measurements over land is more challenging than over the ocean because of large variability in surface parameters determining surface emissivity for the radiative transfer processes. Therefore, efforts were initially focused on the development of a framework to assimilate all-sky GMI radiance data over the ocean. The project has made considerable progress and the framework to assimilate all-sky GMI radiance data over the ocean is currently being tested for implementation in the GMAO's operational forecast system by the end of 2015.

• **In this poster, development and implementation results of data assimilation methodologies to utilize all-sky GMI radiance data in the GEOS-5 system are presented. In addition, future plans to extend this framework to support the PMM Science Team by developing methodologies to assimilate GMI radiance data over land and by investigating methodologies to produce fine scale global precipitation products based on GEOS-5 analyses constrained by GMI observations are discussed.**

2. Goddard Earth Observing System Version 5 (GEOS-5)

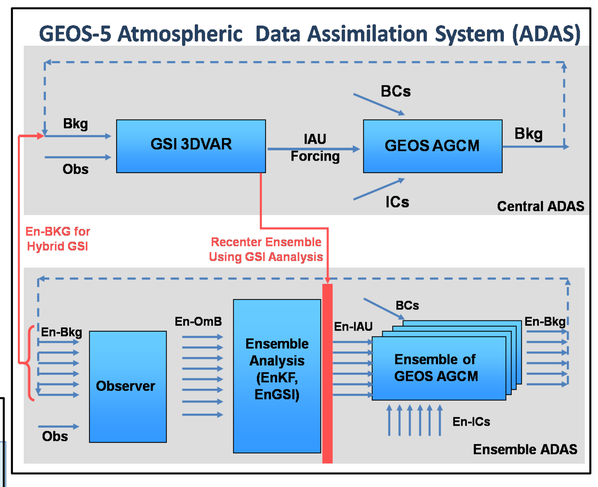


• The GEOS-5 atmospheric data assimilation system (ADAS) is a highly complex yet flexible system composed of GEOS-5 Atmospheric General Circulation Model (AGCM) and the Gridpoint Statistical Interpolation (GSI) analysis algorithm (Kleist et al. 2009).

• The GEOS-5 AGCM is a weather and climate-capable model used for atmospheric analyses, weather forecasts, climate simulations and predictions at various horizontal resolution with 75 vertical layers to 0.01 hPa. The number of vertical layers will be increased to 137 by the end of 2016 (Figure on the left).

• The GEOS-5 AGCM employs a finite-volume cubed-sphere dynamical core (Putman and Lin 2007) for hydrodynamics and the physics package (Molod et al. 2012) includes moist processes, radiation, turbulent mixing and surface processes.

• Notably, the moisture physics package in GEOS-5 will be enhanced with a two-moment cloud microphysics scheme (Barahona et 2014) in the next GEOS-5 AGCM system upgrade scheduled for 2016. **That two-moment scheme will provide estimates of cloud particle size distributions (PSD) in addition to cloud condensate amounts.**



GEOS-5 Forward Processing (FP) Products

INPUT DATA: First-Guess	GEOS-5 Forecasts	2D: sfc pressure, skin T, soil moisture, soil T, snow, fractions of ice, land, lake, and ocean, sfc roughness, 2m,10m, 50m winds, snow depth,.. 3D: pressure thickness, virtual T, ozone mixing ratio, water vapor mixing ratio, cloud liquid, cloud ice, rain water, and snow water mixing ratios, ..
INPUT DATA: Observations	AEROSOLS	Terra & Aqua Atmospheric Optical Depth
	TEMP. & PRESSURE	Radiosonde, Aircraft, Dropsonde, Drifting Buoy, METAR, Land Station
	RADIANCES	AIRS, AMSU-A, HIRS4, ATMS, SSMIS, GOES Sounder, MHS, IASI, CRIS, SEVIRI
	WINDS	Radiosonde, PIBAL, Wind profiler, NEXRAD, Aircraft, Dropsonde, Surface Marine, ASCAT, AVHRR, IR/VIS Cloud Drift, PILOT
	MOISTURE	Radiosonde, Surface Marine, Surface Land, Dropsonde, Buoy, METAR, Aircraft
	GPS Radio Occultation	GRACE-A, TerraSAR-X, METOP-A, COSMIC-1,2,5,6, TANDEM-X, METOP-B
	OZONE	AURA OMI, MLS

OUTPUT PRODUCTS:
Near-real time assimilation products at every 00UTC, 06UTC, 12UTC, and 18UTC
10-day forecasts at every 00UTC
5-day forecasts at every 12UTC
• Horizontal grid: 5/16 X 1/4 degree lon-lat grid
• 3D data are available in 42 pressure levels or 72 model grid layers
• 2D data every hour, 3D data every 3 hours
• Detailed information of assimilation products/forecasts are available in http://gmao.gsfc.nasa.gov/products/

• The GSI combines information from irregularly distributed observations with the GEOS-5 AGCM model state in such a way as to minimize a specified cost function.

• **It is currently based on Hybrid 3D-EnsVar analysis solver (Figure above) and will be upgraded to Hybrid 4D-EnsVar analysis solver by the end of 2015.**

• Figure on the left describes inputs and output products of **the GEOS-5 Forward Processing (FP) stream**, which generates forecasts as well as assimilation products using the most current GEOS-5 system used for near-real time production at NASA GMAO.

3. Assimilation Methodology for All-sky GMI radiance data

New Components added to assimilate all-sky GMI radiance data over Ocean

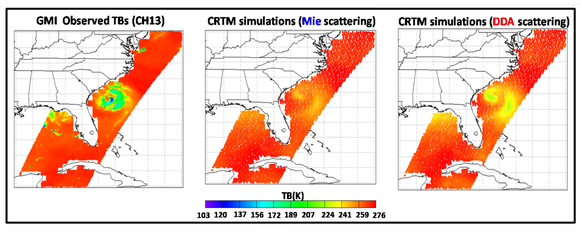
Cost Function $J(x_a) = \underbrace{(x_a - x_b)^T B^{-1} (x_a - x_b)}_{\text{Fit to model background fields}} + \underbrace{(H(x_a) - O)^T R^{-1} (H(x_a) - O)}_{\text{Fit to observations}}$

X_b = Background (first-guess)	Added cloud liquid (ql), cloud ice(qi), rain(qr), snow(qs)
x_a = Analysis	Added ql, qi, qr, qs
O = Observations	New QC gross checks to keep cloud and precipitation affected radiance data
B = Background Error Covariance	Added static B and EnKF B for ql, qi, qr, and qs
R = Observation Error	Developed and assigned observation errors for all-sky GMI radiance data
H = Observation Operator	Evaluate/Enhance CRTM performance in regions with preciptiation
Bias correction : Variational Bias Correction (VarBC)	Bias correction predictors in VarBC: constant, lapse rate, lapse rate^2 to correct air-mass related biases. Cloud liquid water path was removed from the original predictors used in the operational GEOS-5 ADAS.

• Advances in modeling, radiative transfer, and assimilation methods have allowed us to make significant progress in the assimilation of cloud- and precipitation-affected microwave radiances over the ocean.

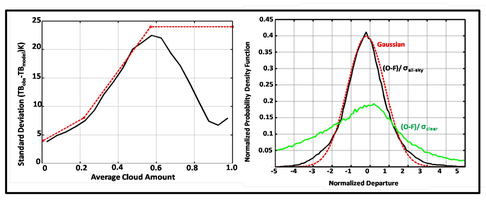
• **These enhancements to the GEOS-5 ADAS are summarized in the figure on the left and a detailed description follows.** GMI observations from channels 3~13 (19~183.3 ±7 GHz) are assimilated over ocean in the all-sky condition. While observations from channels 1 and 2 are being investigated for atmosphere-ocean coupled SST analysis at GMAO, they are not considered in the all-sky experimentation.

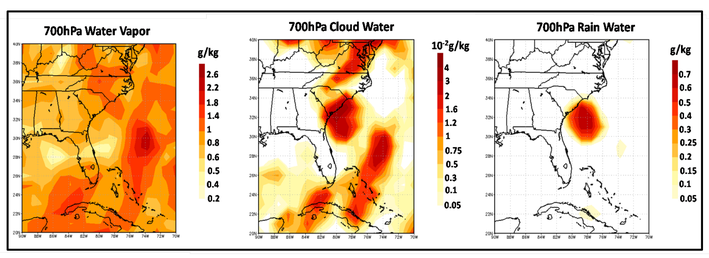
• The observation operator that simulates radiance data in the GSI has been extended to include cloud liquid, cloud ice, rain, and snow fields to be used in the radiative transfer model calculations by the CRTM. The ability of the CRTM to simulate GMI radiances in the regions with cloud and precipitation is illustrated in the figure shown below. Results show that Mie derived cloud scattering parameters were not appropriate for simulating GMI radiances affected by frozen precipitation.



Especially at high frequencies, the computed TBs were too warm relative to the GMI observations. Based on this evaluation, **we replaced the current CRTM cloud coefficient file with a look-up table composed of scattering parameters based on the Discrete Dipole Approximation (DDA) method (Liu 2008). This significantly improved performance of CRTM in precipitating regions.**

• The observation errors for all-sky GMI radiances are estimated based on standard deviation of first-guess departures as a function of cloud water amount following the methodology in Geer and Bauer (2011). **The use of this error assignment method resulted in a near-Gaussian distribution of first-guess departures for all-sky GMI radiances when normalized by their estimated errors (See figure on the right).**

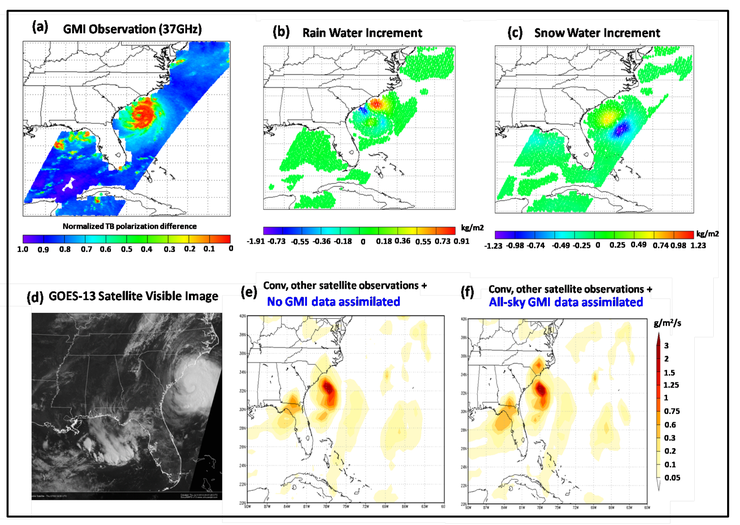




• ql, qi, qr, and qs have been added as analysis variables to assimilate all-sky GMI radiance data assimilation. Therefore, clouds and hydrometeors are now adjusted through the analysis process by the GMI observations. **This allows generation of global analyses of cloud and precipitation analyses** in addition to core meteorological variables (T, q, u, v, p,..)…

• The hybrid 3D-EnsVar analysis algorithm in GEOS-5 ADAS provides flow-dependent and situation dependent background error covariance information for meteorological variables including hydrometeors. **Specifically, this allows for increments of varying water species to be physically consistent across different analysis variables (e.g. between clouds and water vapor) as demonstrated in the figure shown above.**

4. Results: Cloud&Precipitation Analyses and Impacts on GEOS-5 precipitation Forecasts



• The results demonstrated that assimilating all-sky GMI radiance data over the ocean can improve severe weather forecasts from GEOS-5 system.

• For example, impact results from a test case for Hurricane Arthur, which reached hurricane status on 3 July 2014, are shown in the figure on the left.

• In this comparisons between the observations and the modeled cloud, rain, and snow, it was seen that the model underestimates the liquid cloud amount in Hurricane Arthur and displaces the hydrometeors from the storm location.

• By incorporating GMI radiances under all-sky conditions, the analysis moves toward the observations via generation and removal of clouds, rain, and snow as illustrated in the figures (a)-(c).

• Assimilating all-sky GMI radiance data improves the analysis humidity, temperature, and winds in the storm region, which in turn results in improved precipitation 6hr forecasts as demonstrated in the figures (d)-(f).

5. Future Works

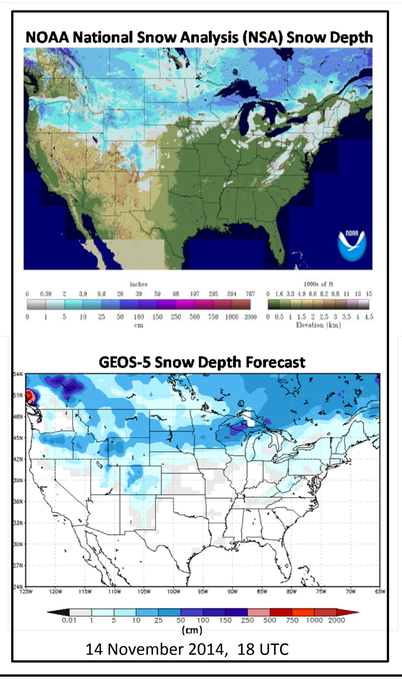
Extended framework to assimilate all-sky GMI radiance data over land

Hypothesis: Assimilating GMI all-sky radiance data over land in the GEOS-5 ADAS will complement GEOS-5 land surface analyses by improving precipitation analyses and forecasts. Gridded precipitation is a key input for the GEOS-5 land surface model, which simulates hydrological processes. Improvements to the land surface model feed back to the assimilation and the quality of surface fields (e.g. skin temperature, soil moisture, and snow coverage). **These improvements will enhance the use of microwave radiance data in both in NWP forecasts and PMM precipitation retrieval algorithm developments.**

Methodologies:

• All-sky GMI radiance assimilation over land requires several advancements beyond the existing ocean all-sky methodology. The most critical, yet challenging aspect of land assimilation is properly assigning contributions from the various surface variables in the radiative transfer model during the analysis process so that information from GMI observations can be projected in the analysis to improve precipitation forecasts over land.

• **We are currently developing methodologies to consider surface contributions from various surface types properly in the radiative transfer model during the analysis process in GEOS-5 ADAS.**



14 November 2014, 18 UTC

Downscaling of GMI observations using GEOS-5

Hypothesis: By combining satellite microwave observations with global atmospheric model simulations, profile-integrated measurements like microwave radiance can be disaggregated to estimate various atmospheric states and precipitation profiles while keeping the relationships between the various fields consistent with the physical laws assumed by the model. In particular, coarse scale observations can be downscaled to estimate finer resolutions of precipitation fields and atmospheric states through **the GEOS-5 downscaling capability**. This effort will be beneficial for many applications such as hurricane modeling studies and land surface and hydrology models and analysis systems.

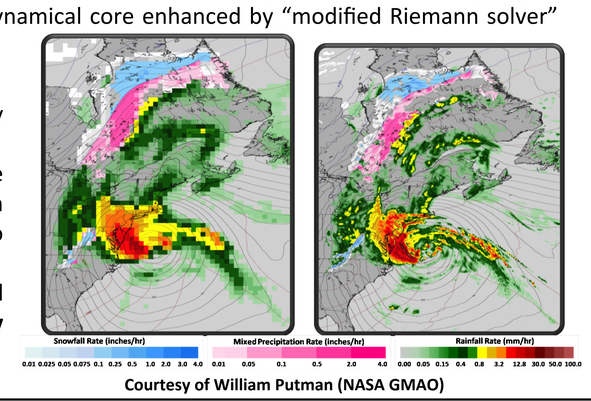
Methodologies:

• At cloud-permitting resolution (1-15km), the vertical velocity can become non-negligible. The use of Lagrangian coordinate system in GEOS-5 non-hydrostatic finite-volume dynamical core enhanced by "modified Riemann solver" removes the potentially severe time-step restriction without ad hoc vertical-velocity damping.

• The physics parameterizations are scale aware in that they dynamically adapt to the horizontal resolution of GEOS-5.

• This multi-scale design allows GEOS-5 to consistently move from medium range weather prediction and data assimilation resolution (~25 km) to cloud permitting resolutions of 12-to 3.5km.

• **Figure on the right provides an illustration of downscaled precipitation (12km resolution) from GEOS-5 constrained by the 50km MERRA-2 analyses during Hurricane Sandy in 2012.**



Courtesy of William Putman (NASA GMAO)